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RESEARCH ON CHARACTERIZATION OF THE UPPER ATMOSPHERE USING LIDAR

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13. ABSTRACT *(Maximum 200 words)*

We describe our three year effort to characterize the upper atmosphere using sodium fluorescence and Rayleigh lidar techniques. We have made progress in the development of sodium fluorescence lidar. We have extended the range of the PL/GPIM fixed base and mobile lidar systems through development of combined analog/photon counting techniques, development of Raman lidar channels, improvement of background rejection and injection locking of transmitter lasers. We have investigated the applicability of lidar to measure changes in the density of excited nitrogen in the lower atmosphere. We have conducted research in Massachusetts, Alaska and Hawaii on high altitude density and temperature characteristics and on the aerosol layer produced by the Mt. Pinatubo volcano. We have improved the reliability, performance and overall productivity of the lidar systems.

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Foreword

This report covers PhotoMetrics' three year effort under contract number F19628-90-C-0175 to characterize the upper atmosphere using sodium fluorescence and Rayleigh lidar techniques. The investigators wish to thank Dr. Phan Dao (PL/GPIM), the contract manager, for his support throughout the program.

1. Program Objectives

The objective of this three year research effort was to characterize the upper atmosphere using sodium fluorescence and Rayleigh lidar techniques. This included extending measurements to higher sensible altitudes than were previously attainable and developing techniques to allow improved spatial and temporal resolution.

Specifically, the program objectives included the following elements:

I. Development of sodium fluorescence lidar, considering both dye and Nd:YAG laser sources of sodium resonant radiation.

II. Extension of the dynamic range of the PL/GPIM lidar systems through:

- Development of combined analog/photon counting techniques to allow improved overall range capabilities.
- Development of Raman lidar channels complementary to the Rayleigh lidar systems to allow improved accuracy of lower altitude measurements.
- Investigation of the applicability of lidar to measure changes in the density of excited nitrogen in the lower ionosphere.
- Improvement of background rejection to extend range capabilities during periods of high sky brightness.
- Investigation of the applicability of injection-locking techniques to the PL/GPIM dye and Nd:YAG laser systems.

III. Research on high altitude density and temperature characteristics of the atmosphere below approximately 80 km using the PL/GPIM fixed and mobile lidar systems.

IV. Examination of methods for improving the reliability, performance and overall productivity of the lidar systems.

2. Summary of Progress in Meeting the Objectives

The following objectives have been successfully completed under the program:

I. Combined analog/photon counting techniques have been developed and used during the ALOHA '93 field campaign.

II. Nitrogen Raman lidar channels have been added to both the fixed and mobile lidar systems. In the fixed base system, one of the old ultraviolet Rayleigh channels was converted to receive 607 nm radiation, the wavelength at which nitrogen Raman scatters 532 nm incident radiation. In the mobile lidar trailer, a 382 nm receiver

channel was installed to collect the nitrogen Raman scattered light from 351 nm incident radiation.

III. Calculations have been performed to investigate the applicability of lidar to measure changes in the density of excited nitrogen in the lower ionosphere. A separate report is being prepared to describe this work in detail.

IV. Gains were made in the rejection of background during periods of high sky brightness. Two approaches were taken. First, we addressed systematic problems in the operation of the piezoelectrically tuned etalon used in the mobile trailer lidar. Second, we replaced that etalon with a temperature-tuned, polarized etalon and attempted to reject the dominant polarization component of the zenith sky with the sun at large zenith angle. This experiment was only partially successful.

V. Injection locking techniques were adopted during the summer 1992 field campaign at Poker Flat, Alaska. This experience has, in part, led to the adoption of injection locking technology for the sodium temperature lidar system presently under development.

VI. Density and temperature data were collected from Rayleigh and Raman measurements of the atmosphere below approximately 80 km. Data were collected with both the fixed base lidar at Hanscom AFB and during field campaigns in Greenland, Alaska and Hawaii. Data were collected to study stratospheric and mesospheric dynamics as well as to provide correlative data to the Upper Atmospheric Research Satellite (UARS) and to various rocket experiments launched from Poker Flat.

VII. Numerous improvements were made to both the fixed base and mobile lidar systems to enhance their reliability, performance and productivity. These improvements included new triggering circuitry, new safety radar veto circuitry, photomultiplier electronic gating and enhancements to the data acquisition software.

VIII. In addition to the planned enhancements and observations, the June 1991 eruption of Mt. Pinatubo provided the surprise opportunity for extensive observations of volcanic dust layers during the contract period.

These topics are discussed in detail in the following sections of this report.

3. Sodium Fluorescence Lidar

The goal of the sodium fluorescence lidar development effort was to build a compact, reliable source of narrow linewidth, tunable sodium resonant radiation. The motivation for this is to make direct measurements of the temperature of the sodium layer that resides at an altitude between 80 km and 110 km, and to use those temperature measurements to infer atmospheric density in the upper mesosphere.

The lifetime of the $3^1P_{1/2}$ excited state of sodium is 16 ns, so the natural linewidth is small compared to the Doppler linewidth. Consequently, the sodium temperature can be inferred from a measurement of the Doppler broadening of sodium within the layer. Figure 1 shows that the hyperfine structure of the sodium D_2 line causes it to be split into two dominant components, and shortcut to measure the Doppler broadening is to measure the cross section at one of the cross section peaks and at the bottom of the valley between the two peaks. To do this, one needs a tunable laser with a linewidth substantially narrower than the Doppler broadened width of the D_2 line itself.

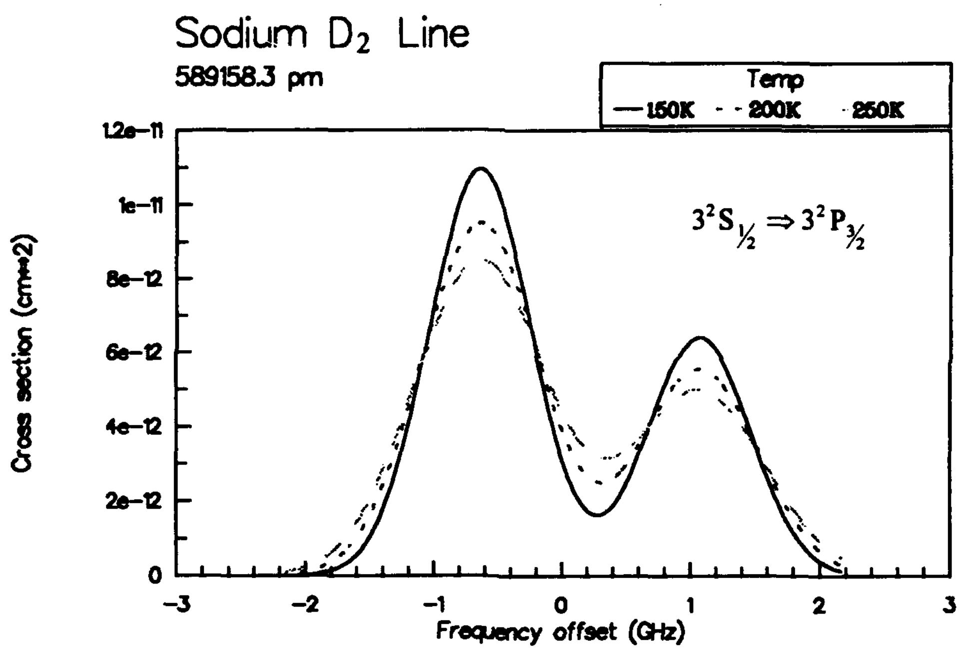

Figure 1. Doppler Broadened Hyperfine Structure of the Sodium D_2 Line.

The approach envisioned was to use a Littman-type grazing incidence dye oscillator, pumped with a Nd:YAG laser, to generate the sodium resonant radiation. The initial laser pulse was to be amplified in a pulsed dye amplifier, also pumped with the Nd:YAG laser. Wavelength monitoring was to be done with the Hovemere wavemeter and with saturation spectroscopy in a heated sodium vapor cell. Wavelength stabilization was to be achieved with feedback electronics controlling a piezoelectrically positioned tuning mirror. The error signal for the feedback electronics was to be generated from a bicell using the variation in angle output beam angle as a function of laser wavelength.

During the first year of the program the grazing incidence laser optical components were purchased and the mechanical components were fabricated at PhotoMetrics. The wavelength locking electronics was designed and some of it was built. Repairs were made to the Hovemere wavemeter. Experiments in damping the sensitivity of the laser to acoustic vibration were performed. The grazing incidence laser lased, but stabilization to the sodium line was never achieved and its performance has not been characterized.

4. Extension of the Dynamic Range of PL/GPIM Lidar Systems

4.1 Development of Combined Photon Counting and Analog Photocurrent Measurement

Conventional photomultiplier photon counting becomes inaccurate at count rates exceeding a few tens of megahertz because the discriminator circuitry is unable to separate photoelectron pulses that are separated by times less than about their pulse width. Analog measurement of the photocurrent is accurate with the high photocurrents that correspond to incident photon arrival rates of 100 MHz and more, but are inaccurate at low incident light levels because there is inadequate discrimination against the equivalent input noise of the amplifier. To take advantage of the full dynamic range available in the photomultiplier signal we need to use both analog measurement and photon counting.

A method for doing this was devised and extensively tested at PhotoMetrics. We used a Hamamatsu R878 photomultiplier and a Pacific Instruments AD6 preamplifier. Normally one feeds the preamplifier output into either a discriminator for photon counting or into an amplifier and an analog-to-digital converter for analog measurement. Both the discriminator and the analog amplifier have a 50Ω input impedance. We found that the output impedance of the AD6 preamplifier was low enough that its output signal could be split between two 50Ω loads and be reduced in amplitude by only about 10%. This was sufficient to drive both the AD6 discriminator (with a slightly lower threshold discriminant) and a DSP 1020 amplifier. The output of the 1020 was fed to a DSP 2112 analog-to-digital converter with averaging memory and the output of the AD6 discriminator was fed to a DSP 2110 multichannel scalar with averaging memory. The system was tested for linearity over the full dynamic range of the photomultiplier tube.

This dual analog/photon counting measurement system worked flawlessly in the field during the ALOHA '93 campaign at Maui, Hawaii. Here, the lidar receiver was mounted on the AMOS telescope, and 100 feet of cable ran between the AD6 preamplifier and discriminator and the DSP CAMAC electronics. This great length of cable did not compromise the signal. The combined analog and photon counted signals were used to extract the maximum altitude range from the lidar data. Combined lidar return profiles showed the analog and photon counted profiles could be combined with no discontinuity in slope after amplitude normalization. The analog measurements proved to be particularly valuable for measurements of the relatively low altitude dust remnant from the eruption of Mt. Pinatubo, while the photon counting profiles provided temperature and density measurements up to approximately 80 km altitude.

4.2 Development of Raman Lidar Channels

Nitrogen Raman receiver channels were added to both the fixed base lidar system and the mobile lidar trailer. The Raman scattering cross section of nitrogen is roughly three orders of magnitude smaller than the Rayleigh cross section. Thus, the Raman channel can be used in photon counting mode for low altitude data that would saturate the Rayleigh channel. What is more important, the Raman receiver channel is blind to Mie scattering from aerosols except for the losses caused by particulate scattering. Accurate density profiles can be obtained in the troposphere where Mie scattering from aerosols and dust render inaccurate the density profiles extracted from Rayleigh lidar returns. With the combined Rayleigh and Raman density profiles, temperature profiles from the troposphere through the mesosphere can be gotten.

The Raman channel on the mobile lidar trailer was planned for the 1991 winter measurement campaign in Greenland. The Rayleigh transmitter used for that campaign was the xenon fluoride excimer laser operating at 351 nm. The wavelength of the nitrogen Raman shifted is 382 nm. The trailer receiver was modified to accept a thin dichroic filter, an interference filter and a second cooled photomultiplier housing. It was necessary to use a thin dichroic to minimize the lateral displacement of the transmitted beam from the receiver optic axis. The dichroic was mounted ahead of the receiver shutter, so only the Rayleigh channel was shuttered.

Due to a problem related to the specification of the dichroic the Raman channel failed to operate correctly during the Greenland campaign. A proper dichroic was acquired for the 1992 winter measurement campaign in Alaska. Both Rayleigh and Raman density profiles were collected during the campaign. Thirty kilometers was chosen as the normalization altitude, because that altitude was above the Pinatubo aerosol layer, but low enough for a strong Raman channel signal. The use of the two channels of data facilitated the extraction of continuous density and temperature profiles from the middle troposphere to the upper mesosphere.

In the fixed base lidar system a Raman channel was installed as part of the UARS correlative measurement effort. The fixed base system uses a Nd:YAG laser at 532 nm; the wavelength of the nitrogen Raman shifted return is 607 nm. To install the Raman channel, the receiver was removed from the one meter telescope and brought to PhotoMetrics. Filters and dichroics from one of the old ultraviolet channels were removed. A dichroic mirror, three folding mirrors and an interference filter for the 607 nm channel were installed. Baffling was installed to prevent contamination of the Raman signal with scattered Rayleigh return light. A new photomultiplier mount was installed for a cooled Gallium Arsenide photomultiplier, and lenses were installed to match the beam to the photocathode position. While we had the receiver apart, we cleaned the optics that remained, particularly the first lens, which was covered with oil from the shutter wheel bearings. The receiver was returned to operation and both Rayleigh and Raman channels work well.

A 607 nm Raman channel was installed on the mobile lidar receiver for the ALOHA '93 measurement campaign at the Air Force Maui Optical Station (AMOS). This channel was in a different location than the original Raman channel because of physical constraints on the receiver geometry within the AMOS telescope instrument bay. It was tightly baffled to prevent contamination of the Raman signal with scattered Rayleigh return light. The Raman channel return was used in conjunction with the ALOHA '93 Rayleigh channel return to produce continuous density and temperature profiles from middle tropospheric to upper mesospheric altitudes. The Raman data is also available to aid in the analysis of the Pinatubo dust layer data collected in the Rayleigh channel.

4.3 Investigation of Ionospheric Lidar

Calculations were devoted to assessing the feasibility of measuring the relative densities of excited nitrogen in heated and unheated atmospheres. The goal is to use the 4-2 band of the first positive system of nitrogen at 773.7 nm, thus enabling use of the lidar as a diagnostic tool during ionospheric RF heating experiments. The detailed calculations have been submitted as a separate Phillips Laboratory technical report and are being prepared for submission to the journal *Radio Science.*

4.4 Improvement of Background Rejection

Sky background was the dominant noise term in much of the data collected in Alaska and Greenland, and efforts were taken to reduce the sky background level. The narrow bandpass filter used in Greenland and during the 1991 summer Alaska campaign was a Burleigh piezo-driven etalon with a 40 pm FWHM. This did a fair job of reducing background, but it suffered from several problems. Its center wavelength was prone to drift, so a complicated locking scheme was devised using a sodium hollow cathode lamp. The locking scheme, which ramped the etalon piezos between laser shots, excited the natural 1.6 kHz resonance of the piezos, resulting in a modulation of the signal. Also, relative drift of the piezo thickness' caused the signal throughput of the etalon to degrade over time.

Several attempts were made to eliminate the 1.6 kHz oscillation, including acoustic isolation of the etalon, electronic filtering of the ramp signal and active damping. None worked. We found that the signal modulation could be minimized with careful attention to alignment, and we developed a new alignment procedure using a He-Ne laser.

For the 1992 summer campaign we replaced the Burleigh etalon with a 50 pm FWHM DayStar filter. This filter encompassed a temperature-tuned mica etalon and a thin film interference filter. The temperature tuning was quite stable and active feedback was not required. The DayStar filter was supposed to transmit only one linear polarization state of light, so we endeavored to eliminate a large portion of the arctic sky background by aligning the polarization of the transmitted laser beam perpendicular to the dominant polarization component of the sky. A motorized rotation mount for the DayStar filter was installed in the trailer receiver. Unfortunately, the polarization dependence of the DayStar transmission was not as good as advertised, and the additional sky background rejection

obtained with this scheme was small. Background was reduced by 25%, while a 67% reduction was expected based on calculation of skylight polarization.

4.5 Investigation of Injection-Locking Techniques

Injection locking was used aboard the mobile lidar trailer during the 1992 summer measurement campaign in Alaska. We had use of the first Spectra-Physics GCR-5 laser, which was injection seeded with a Lightwave Electronics Miser-based seed laser. We observed that frequency stability, linewidth and beam mode quality were substantially improved over the unseeded Quantel laser used previously. The frequency stability was a particular asset, as it made it easier to keep the receiver bandpass centered on the transmitted wavelength. We did not have an opportunity to test the injection seeded laser as a dye laser pump, but the improved beam quality will certainly result in improved dye laser pumping efficiency.

5. Research on High Altitude Density and Temperature Characteristics of the Atmosphere

PhotoMetrics supported high altitude density and temperature measurements with the fixed base lidar facility, including collection of correlative data for the UARS program. We also supported the following campaigns with the mobile lidar trailer:

- Sondrestrom, Greenland, Winter and Spring, 1991. Temperature and density measurements, observation of stratospheric warming events.

- Poker Flat, Alaska, Summer 1991. Temperature and density measurements with daylight system. Temperature and density measurements, search for noctilucent clouds. During this campaign we were fortunate to observe the arrival of the Pinatubo aerosol cloud over Fairbanks on 12 August.

- Poker Flat, Alaska, Winter 1992. Temperature and density measurements, collection of correlative data in support of a NASA/Clemson University barium release rocket experiment, observation of Pinatubo dust layer.

- Poker Flat, Alaska, Summer 1992. Temperature and density measurements using high power, injection seeded Nd:YAG transmitter and daylight system, search for noctilucent clouds, collection of correlative data in support of University of Michigan rocket experiments, also exploring noctilucent cloud properties, observation of Pinatubo dust layer.

- AMOS, Maui, Hawaii, Summer 1993. Temperature and density measurements, observation of spatial inhomogeneities in Pinatubo dust layer.

The following publications and presentations resulted from these measurement campaigns:

Application of the Rayleigh Lidar to Observations of Noctilucent Clouds, J. W. Meriwether, R. Farley, R. McNutt, P. D. Dao, W. Moskowitz, G. Davidson and M. Burka, Journal of Geophysical Research, v.98 n.D8, 20 August 1993.

Rayleigh/Raman Greenland Lidar Observations of Atmospheric Temperature During a Major Arctic Stratospheric Warming Event, P. Dao, G. Davidson, R. Farley, R. McNutt, J. Meriwether and W. Moskowitz, Proc. 16th ILRC, NASA CP 3158, 1992.

Elastic and Raman Lidar Temperature Measurements from Poker Flat, Alaska, During February 1992, M. Burka, P. Dao, G. Davidson, R. Farley, J. Meriwether and A. Wilson, Proc. 16th ILRC, NASA CP 3158, 1992.

Rayleigh Lidar Measurements and Noctilucent Clouds, M. Burka, W. Moskowitz, G. Davidson, J. W. Meriwether, R. McNutt, R. Farley and P. D. Dao, Optical Remote Sensing of the Atmosphere 1991 Technical Digest, November 1991.

Pinatubo Dust Observations from Fairbanks and Boston, M. Burka, P. D. Dao, G. Davidson, R. Farley, R. McNutt, J. W. Meriwether and A. Wilson, Optical Remote Sensing of the Atmosphere Technical Digest Addendum, November 1991.

6. Improvements to the Reliability, Performance and Overall Productivity of the Lidar Systems

Many of the improvements made to the mobile and fixed base lidar systems have been discussed in the sections above. In particular, the addition of Raman channels to both systems and improvements made to the trailer daylight receiver resulted in improved performance. Additional enhancements are as follows:

- Electronic Gating. For historical reasons, the mobile lidar trailer operated with a master clock to which the laser, receiver and data acquisition were slaved. For the receiver, this involved phase lock loop circuitry controlling a shutter wheel, and the system suffered from jitter. We developed electronic gating for the trailer receiver and built a vastly simplified and much more reliable timing and triggering circuit for the mobile trailer lidar.

- Improved Safety Radar Threshold Detection. The old, unreliable safety radar threshold detection circuit was replaced with a simpler, more versatile circuit aboard the trailer.

- Data Acquisition Enhancements. Several revisions to the CAMX software series resulted in more efficient data storage, IDL-readable date coding of the data files and an easier to use software interface.

- Timing and Triggering circuitry. Numerous repairs were made to the timing and triggering circuitry in the fixed base lidar system. These were mostly patches, however. The fixed base electronics is nearing the end of its useful life and consideration should be given to its replacement.

- Miscellaneous Trailer Enhancements. Remote computer monitors were set up during the 1992 campaigns at Poker Flat. One monitor near the lidar receiver assisted the operator in aligning the lidar beam to the telescope. A second remote monitor was installed in the Poker Flat Optics Laboratory so that Poker personnel could observe lidar returns. A lot of unused cabling was removed from the trailer, resulting in easier access to the cabling that is still in use. A persistent memory problem on the trailer computer was, at long last, diagnosed and corrected.

7. Summary

We have achieved nearly all the objectives set forth in the contract proposal. We succeeded in extending the dynamic range of the PL/GPIM lidar systems, in collecting high altitude density and temperature data, in disseminating that data in print and through conference presentations and in enhancing the reliability, performance and productivity of the lidar systems. In addition, we enjoyed the fortuitous discovery of the arrival of the Pinatubo dust cloud over Fairbanks and of many productive observations of the Pinatubo layer over Boston, Fairbanks and Maui.